7. Conclusions and Suggestions for Future Work

7.1 Summary

This work consists of two major parts: the experimental characterisation of multiphase gas-liquid flow in a narrow rectangular column and the validation of theoretical models against the experimental data.

The experimental work includes construction of the flow regime map and measurements of pressure drop, gas volume fraction, interfacial area, bubble properties, liquid velocity and turbulent Reynolds stresses. These parameters were collected in a narrow rectangular column, operating under co-current upflow regime in two situations: without packing and with packing placed in a structured way. To obtain unbiased, high-accuracy experimental data, non-intrusive techniques, such as pressure transducers, LDV, BIV and image processing, were used. The data was collected at various flow conditions, including bubbly, churn-turbulent and annular regimes in stagnant and flowing liquid. Further, the hydrodynamic parameters were mapped at different axial and lateral positions in order to obtain their 2D distribution and a clear picture of the axial flow development. Therefore, the resulting experimental database carries valuable information for CFD simulations and future theoretical model validation. The main hydrodynamic parameters for the unpacked and the packed columns were compared to show the major differences between the hydrodynamics in both cases. The experimental data collected in the packed narrow
column is probably one of the most relevant contributions of this work, since this type of experimental data is very sparse in the literature.

The numerical validation of various theoretical models was carried out by using commercial CFD software – CFX 4.2. In order to closely simulate the real flow conditions and to allow rigorous comparisons of all tested models, the boundary conditions at the inlet were set according to the experimental data. Then, the predicted lateral profiles of the most important hydrodynamic parameters were compared with the experimental ones. For the unpacked column various alternative approaches were examined and compared with the experimental results: laminar versus turbulent; 2D versus 3D; steady versus dynamic. Further, the effect of lift forces and turbulence on the phase distribution was examined.

After this brief review of the performed work, the main concluding remarks for both the experiments and the simulations follow.

7.1.1 Concluding Remarks from the Experimental Work

Flow regime transitions, determined by visual observation, were compared with available theoretical models and published experimental data. Since the flow regime transitions depend on the column geometry and on the transition criteria, relatively large discrepancies between the various models and experimental transitions were obtained. On the basis of these visual observations, the major conclusions are following:

• Due to decreased freedom of motion, the bubble–slug transition in 2D column occurs at lower gas velocities than in 3D columns,

• The presence of packing increases the range of gas flow rates at which bubbly flow occurs; this is an important aspect for industrial applications of packed columns,

• The bubbly-slug transition in the packed column is more sensitive to the liquid superficial velocity, that is, the range of bubbly flow grows faster with increased liquid velocity than in the unpacked column.

The pressure gradient in single and two-phase flow was obtained using a differential pressure transducer technique. The measured friction factors in single and two-phase flow showed good agreement with available theoretical predictions. Two-phase pressure drop was correlated by the Lockhard-Martinelli and the Chisholm-Laird correlations. These
Conclusions and Suggestions for Future Work

Correlations provided very good prediction of the pressure gradient for the unpacked narrow column. However, when used for the flow in the packed column, these standard correlations had to be slightly modified to improve their predictive capabilities.

For the imaging studies, a simple processing technique was developed that permits direct simultaneous measurements of gas volume fraction, interfacial area, bubble velocities and bubble size parameters. In order to accurately determine the gas volume fraction by image processing, the transversal bubble shapes were visualised by a PIV camera. If these transversal bubble shapes are taken into account in the calculation of the gas volume fraction from imaging, good agreement with the gas volume fraction, indirectly measured from the dynamics of pressure fluctuations, was obtained. Further analysis of imaging and BIV results revealed some interesting observations that can be summarised below:

- Strong migration of gas towards the column centre was observed, mainly in the unpacked column. In the packed column, the peaks of gas volume fraction near the column centre are not so pronounced but the overall magnitude of gas volume fraction was found higher than in the unpacked column at the same flow conditions. The measured gas volume fraction was correlated by the drift flux model for slug, churn and annular flow regimes.

- A relationship between the gas volume fraction and the interfacial area was reported for various flow regimes. A nearly linear dependence between these two parameters in both the unpacked and packed column was found. However, the presence of packing substantially increases the interfacial area and the relationship between $\alpha$ and $a_i$ then depends on the liquid flow rates.

- Measured lateral profiles of the equivalent bubble diameter indicate that large bubbles concentrate near the column centre. This predominantly happens in the unpacked column with zero liquid inflow, but the uniformity of the bubble size increases with higher liquid velocity. In the packed bed, the bubble size was found almost constant over a broad range of flow conditions and the mean bubble diameter was slightly smaller than in the unpacked column. Further, the presence of packing narrows the bubble size distribution and helps to maintain it practically identical at different axial positions.
• Besides the bubble diameter and bubble velocity, another practical data concerning the bubble shape was determined by BIV technique. The two-dimensional plots of these shape factors showed that bubbles of more circular and regular shape were found in the zones of the liquid back-flow, i.e. near the column walls. Further, bubble regularity increases with the liquid velocity.

• Single bubble rise velocity in the 2D column and stagnant liquid are almost identical to the bubble rise velocity observed in 3D columns. This confirms that the bubble motion is driven mainly by inertia force, thereby the effect of viscous and interfacial forces is of secondary importance.

• The bubble swarm velocity exhibits strong dependency on the gas volume fraction and the liquid superficial velocity. Therefore, it was correlated by the relationship proposed by Ishii and Zuber (1979) with an empirical correction accounting for the effect of the liquid superficial velocity. Bubbles in the packed column rise with smaller velocity than those in the unpacked column. This results in increase of the contact time between the phases.

The bubble diameter and bubble velocity profiles were also measured in a system containing a surface-active component – Rhodamine B. It was shown that the addition of the surfactant has similar effect on the multiphase hydrodynamics as the presence of packing. Bubble size and bubble velocity decreases considerably and back-flow suppression was observed. Moreover, the addition of the surfactant resulted in an increased uniformity of the phase distribution and higher magnitude of the gas volume fraction in the unpacked column. The impact of the surfactant on the hydrodynamics of the packed column is of less importance although slightly narrower bubble size distributions than in the pure water were observed.

Backscatter LDV measurements were performed with a fast-response photodiode detector to discriminate between the signal coming from the liquid and the gas phases. The 2D maps of the rejected signal revealed that the occurrence of an ambiguous signal is somehow proportional to the local gas volume fraction. Two components of the liquid mean velocity and the Reynolds stresses were mapped for limited number of gas and liquid rates including both the homogeneous and the heterogeneous regimes. The LDV data in the packed column was collected from two qualitatively different locations: from the passages between two adjacent packing particles; and from the chambers created by four
adjacent packing particles. The most important observations from the LDV experiments are the following:

• The lateral profiles of axial velocity confirmed a relatively strong liquid recirculation that decreases with increased liquid flux.

• The turbulence in the unpacked column was found highly anisotropic and strongly proportional to the local gas volume fraction. The normal Reynolds stresses in the direction of flow were more than two times higher than the corresponding lateral stresses. The small magnitude of the shear Reynolds stresses indicated a relatively weak correlation between the axial and the lateral liquid velocity fluctuations.

• The liquid velocity fields in the packed column showed a decreased liquid phase recirculation and higher shear Reynolds stresses if compared with the unpacked column. The normal Reynolds stresses in the packed column are almost of the same magnitude in both lateral and axial directions, thus indicating that the packing helps to maintain the turbulence isotropy.

This vast experimental database containing the main hydrodynamic parameters from various axial positions permitted performing relatively rigorous validation of the models currently incorporated in the CFX software. The concluding remarks from the simulations are given in the next section.

7.1.2 Concluding Remarks from CFD Simulations

Simulations were performed in the form of numerical experiments, where the various effects, such as lift forces, turbulence parameters and importance of the third dimension in the model geometry, were examined. Based on comparison with the experiment data, the best matching model was then chosen and tested for different flow conditions. In order to decrease the number of model parameters, the effect of bubble coalescence and break-up was neglected and the concept of uniform bubble size was adopted instead. Despite of this simplification, the present model indirectly includes the effect of bubble-bubble interactions in the formulation of the drag coefficient whose magnitude depends on the local gas volume fraction, which was also confirmed by the experiment.

The main conclusions from the simulations are summarised bellow.
CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

• Preliminary CFD simulations of single-phase flow in laminar regime were carried out to examine the column geometry and boundary conditions settings. After some rearrangements concerning the column geometry, good agreement with velocity profiles and pressure drop determined experimentally was obtained.

• 3D two-phase steady-simulations with zero lift forces showed discrepancies in phase distribution and turbulence properties. When the Bernoulli-like lift force, (Ranade, 1997) was included, a good match with the experimental gas phase distribution and velocity profiles was obtained.

• 3D steady simulations with the $k-\varepsilon$ model showed moderate agreement with the liquid velocity profiles and underestimation of the gas volume fraction. The problem of these simulations is the strong underestimation of the turbulence level compared to the experimental data. The addition of the bubble-induced turbulence term in the $k-\varepsilon$ model did not significantly affect the predicted kinetic energy profiles. This was attributed to the artificial wall-law boundary condition that strongly dampens the turbulent kinetic energy near the walls. The 3D steady simulations were performed on a relatively coarse grid, whose refinement did not reveal any significant changes in the predicted profiles of the main hydrodynamic parameters.

• 2D turbulent simulations provided improved prediction of the turbulence level but on the other hand, disagreement in phase velocities and gas volume fraction profiles was observed. This turbulence was mainly generated by the work of shear stresses and including of the bubble-induced turbulence term resulted in strong overestimation of the measured values. To decrease the turbulence level and the discrepancies in phase velocities, a body force that simulates the effect of the transversal shear stress was included in the momentum equations. An improved prediction of the main hydrodynamic parameters was observed but the predicted turbulence profiles showed unsatisfactory agreement with the experimental data.

• 2D transient laminar simulations predicted a highly dynamic flow pattern with strong dispersion of the gas phase. The time series of the axial velocity showed similar spectrum as the experimental one in low-frequency interval but due to excluding the high-frequency oscillations, the predicted level of turbulent kinetic energy was not high enough to match with the experimental one. 3D transient simulations showed only small large-scale oscillation of the gas plume that cannot generate sufficient level of
turbulent kinetic energy. From these results, it was concluded that the large-scale movement of the gas plume most likely contributes with only a small part to the overall turbulence intensity and most of the turbulence in the narrow column is generated at a small-scale level.

• The separate modelling of the bubble-induced turbulence, similar to the model suggested by Lopez de Bertodamo (1994), provided satisfactory prediction of all examined parameters. This model includes an additional transport equation for the bubble-induced turbulent kinetic energy that can be anisotropically distributed to the momentum equations in the form of the Reynolds stresses. The force resulting from the lateral distribution of normal Reynolds stresses has a high impact on the gas distribution but it was found to be not sufficient to predict the inward bubble migration. This model was also examined for flowing liquid conditions and good agreement with the experimental data was obtained.

CFD simulations revealed that the theoretical models still lack knowledge about various phenomena, such as phase distribution and turbulence in two-phase flow. These are mostly modelled in semi-empirical ways that are suitable only for restricted ranges of flow conditions. Therefore, it should be stressed that both the experimental research and the numerical predictions should continue in order to contribute to a better understanding of the two-phase flow hydrodynamics and to improvement of the performance of two-phase columns. Possible directions for extension of this research are suggested in the next section.

7.2 Suggestions for Future Work

Two-phase flow remains an interesting and challenging area for current research. Up till now, this research has been mostly restricted to the characterisation and simulation of homogeneous regimes with negligible bubble-bubble interactions. An extensive experimental database has been collected for these regimes and the models have showed satisfactory predictive capabilities.

However, many industrial gas-liquid columns operate in churn-turbulent regimes, where the bubble-bubble interactions are important and turbulence generated by bubbles is significant. Therefore, future research should be extended towards the better understanding of heterogeneous gas-liquid flow. It means that both the experimental and theoretical
research should be driven towards the explanation of bubble-bubble interactions, study of small-scale phenomena such as bubble wakes and the turbulence generated by bubbles. Primarily, their effect on the phase distribution should be elucidated.

Narrow flat multiphase columns provide favourable conditions for this kind of research. They allow easy flow visualisation and obtaining of accurate experimental data. However, certain aspects of the two-phase flow in narrow columns are most likely different from those in 3D geometries. Therefore, to extend the results obtained from 2D flow to 3D columns, a good understanding of these differences is necessary, which can be only ensured by careful comparison of 2D and 3D experimental results.

From the reasoning introduced before and the analysis of the reported results, the following suggestions for the future research in the 2D gas-liquid column emerge.

• The instantaneous liquid velocity field in the vicinity of bubbles simultaneously with the bubble velocity should be measured by PIV technique. To study the coalescence and break-up phenomena, an high-speed video camera is recommended since the standard PIV technique cannot capture the dynamics of these processes. A further examination of the surfactant effect on the bubble break-up and coalescence is recommended to better understand these phenomena.

• Experimental characterisation of a 3D cylindrical column is needed to perform comparison of the 2D experimental data with the data from the 3D column. This comparison should help to determine the limits of a possible extension of the 2D results to the 3D situation.

• Experimental study of the flow in the packed column can be extended by using different packing particle shapes, layout structures, and different porosities. The resulting experimental database could be used for correlation and simulation purposes. Further, experiments with a tracer or simple chemical reaction in the column with and without packing should be performed. The principal objective is to create sufficient experimental database for the numerical simulations and to show the effect of packing on the overall mass transfer and on the bubble reactor performance.

• Future simulation work should include the effect of bubble size distribution on the column hydrodynamics. One of the progressive solutions appears to be the model
developed by Krishna et al. (1999) for churn-turbulent regime or the MUSIG model developed by Lo (1999) that accounts for bubble-bubble interactions.

- Volume-of-Fluid technique has become recently a very attractive simulation tool since it allows studying the hydrodynamics of single bubble or small bubble swarm with high accuracy. It allows direct calculation of the pressure and stress distribution along the bubble surface and subsequently, the lift and drag forces acting on a bubble. Therefore, simulations by using of this approach are recommended, since they can provide some additional information about the lift forces effect and bubble-induced turbulence.

- Finally, CFD simulations of the packed column should be performed with accounting for an additional resistance due to presence of packing. After resolving the hydrodynamic problems, further simulations should include mass transfer or chemical reaction effects. Their validation with the experimental data and optimisation of the packing particle shape and the packing structure can have direct impact on the design of industrial two-phase packed rectors.